EXPERIMENTAL STUDY OF THE INFLUENCE OF SPATIAL INHOMOGENEITIES IN UNDERWATER ACOUSTIC PROPAGATION

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Abstract: *The authors investigate here the problem of acoustic wave transmission through a spatially fluctuating medium. Although experimental and analytical study are available in the literature, the objective is here to reproduce in tanks some phenomena, such as linear internal waves, that are responsible for horizontal fluctuations of the depth dependant sound speed profile and de-coherence effects of the propagated acoustic signals.*
The idea is to use acoustic lenses, or wax plates presenting a specific profile, to obtain ultrasonic pressure fields comparable to what can be observed in the case of lower frequency acoustic wave travelling through linear internal waves.
Analytical studies allowing to compare dimensionless quantities relative to the measured field with Flatté's classical typology are developed as a support for the experiment.
We believe that being able to reproduce these phenomena in controlled environment will be of great help not only to understand and anticipate the perturbations observed on the acoustic wave fronts, but also to work on some corrective signal processing techniques.
We focus here on the observation of the wave fronts of the perturbed signals and on the influence of the perturbations on a focalization algorithm.

Keywords: *De-coherence, Tank Experiments, Fluctuations, Dimensionless Analysis.*

1. INTRODUCTION

For a long time, the subject of wave propagation through fluctuating media has been studied by physicists [1] [2]. In order to perform accurate prediction on the acoustic pressure field, stochastic studies are needed [3] [4]. The results of such studies showed that fluctuations of the depth-dependent sound speed profile can induce perturbations in the underwater sound propagation, such as the appearance of caustics [5][6][7].

Moreover, these perturbations of the pressure field are responsible for some degradation of the performances of acoustic arrays [8][9][10][11]. Being able to conduct measurements of sound waves fluctuations of a controlled environment will be a great help to relate the observations in the field with numerical models and to anticipate for corrective signal processing techniques.

In this paper, we will first present the scientific approach, including analytical considerations, techniques developed in order to measure the perturbations of the signals and experimental configuration, and then we will focus on some experimental results.

2. SCIENTIFIC APPROACH

The idea developed here is to be able to reproduce, at the ultrasonic scale, pressure fields comparable to what would be obtained in the case of propagation of lower frequency sound wave through a fluctuating medium, such as a linear internal waves field. We expect here to be able to provide qualitative and dimensionlessly quantitative parameters that we can relate to Flatté's theory of unsaturated and saturated sound fields [4][5][6].

We propose expressions for the average number of eigen rays reaching a receiver as a function of the normalized standard deviation of the divergence of the ray. The divergence is also obtained analytically starting from the Fourier transform of standard parabolic equation applied to the moment of order 2 and 4 of the acoustic pressure field. Simulation tools, such as a ray tracing program, allow us to compute the number of eigen rays we can measure at a given receiver position and the phase difference between the eigen rays. Results from experimental measurements are studied along with these analytical and simulation considerations.

2.1 Analytical Results

The starting equation of our work is the extension to 3D of the 2D standard parabolic equation applied to the Fourier transform of the 2nd and 4th order moment of the pressure field (respectively denoted J_2 and J_4):

$$\frac{\partial \mathrm{J}_2}{\partial x}+\theta\frac{\partial \mathrm{J}_2}{\partial z}+\varphi\frac{\partial \mathrm{J}_2}{\partial y}+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta^2}\Big|_{0,0}\left[\frac{\partial^2\mathrm{J}_2}{\partial\theta^2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\upsilon^2}\Big|_{0,0}\left[\frac{\partial^2\mathrm{J}_2}{\partial\varphi^2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta\partial\upsilon}\Big|_{0,0}\left[\frac{\partial^2\mathrm{J}_2}{\partial\theta\partial\varphi}\right]=0, \tag{1}$$

And

$$\frac{\partial \mathrm{J}_4}{\partial x}+\theta_1\frac{\partial \mathrm{J}_4}{\partial z_1}+\varphi_1\frac{\partial \mathrm{J}_4}{\partial y_1}+\theta_2\frac{\partial \mathrm{J}_4}{\partial z_2}+\varphi_2\frac{\partial \mathrm{J}_4}{\partial y_2}$$
$$+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta^2}|_{0,0}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\theta_1^2}+\frac{\partial^2 \mathrm{J}_4}{\partial\theta_2^2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\upsilon^2}|_{0,0}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\varphi_1^2}+\frac{\partial^2 \mathrm{J}_4}{\partial\varphi_2^2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta\partial\upsilon}|_{0,0}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\theta_1\partial\varphi_1}+\frac{\partial^2 \mathrm{J}_4}{\partial\theta_2\partial\varphi_2}\right] \tag{2}$$
$$+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta^2}|_{z_1-z_2,y_1-y_2}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\theta_1\partial\theta_2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\upsilon^2}|_{z_1-z_2,y_1-y_2}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\varphi_1\partial\varphi_2}\right]+\frac{1}{2}\frac{\partial^2\phi}{\partial\zeta\partial\upsilon}|_{z_1-z_2,y_1-y_2}\left[\frac{\partial^2 \mathrm{J}_4}{\partial\theta_1\partial\varphi_2}+\frac{\partial^2 \mathrm{J}_4}{\partial\theta_2\partial\varphi_1}\right]=0.$$

where ζ and υ stand respectively for the vertical and horizontal deviation, θ and φ are the bearing and elevation angles. In the 4th order moment case, these variables are associated with a subscript corresponding to the coordinates system of each emitted ray. ϕ represents the intercorrelation of the fluctuations of sound speed.

We notice that equations (1) and (2) present the same "structure": terms of transport (first three terms in (1), first five terms in (2)) and terms of angular diffusion (last three terms in (1) and last six terms in (2)).

Using equations (1) and (2) and relationships between moments of the random variables translating for the variance of the coordinates and the slope of the emitted rays, we are able to establish an expression for the mean divergence of the ray, denoted U. The divergence is an important quantity, since its statistical properties allow us to derive the expression for the average number of eigen rays:

$$\langle N\rangle = erf\left(\frac{\sqrt{2}}{s}\right)+s\sqrt{\frac{2}{\pi}}e^{-\frac{1}{2s^2}}, \tag{3}$$

where $s=\sigma_U/<U>$ is the normalized standard deviation of the divergence. Since the divergence can be evaluated knowing the values of the vertical and the horizontal correlation length of the sound speed fluctuations, respectively denoted L_V, L_H, the distance between source and receiver and the variation of sound speed $\delta c/c_0$, we are able to calculate the number of eigen rays corresponding to a given medium presenting fluctuations of the sound speed.

2.2. Simulation Tools and Experimental Configuration.

In order to be able to anticipate for the results of an experiment, simulations are useful tools. In our case, a ray tracing program gives us some information about the way the emitted signal would be distorted when traveling through the considered medium.

We developed a ray tracing program able to propagate rays through a given surface and to take into account the sound speed of the material composing this surface. The program does not provide the acoustic pressure field at the output of the surface, but it gives information on the appearance of caustics or focal points. Strictly speaking, this propgram predicts the effects of acoustic lens with arbitrary shapes. But due to refraction of rays, these phenomena are similar to what should occur at sea in presence of linear internal waves.

Moreover, we are able to determine the number of eigen rays crossing the receiver (given the hydrophone position in 3D and its radius). The phase shift of the eigen paths can also be extracted. It is important to emphasize the fact that this kind of tool is very important to anticipate for the regime of fluctuation to which the measured signal in the experimental framework would belong. Indeed, dimensionless parameters such as those presented by

Flatté are not directly measurable on experimental data. The experiment itself consists of transmitting an acoustic pulse centered at $f_0 = 500kHz$ at a distance $d_{S/P}$ from a surface placed between the source and receiver, separated by a distance $d_{S/R}$. The hydrophone is placed on a motorized arm allowing motion in three dimensions. Thus, we are able to realize virtual antennas by small displacements of the hydrophone. The cases of vertical and horizontal antennas at different distances $d_{S/R}$ will be studied here. Figure 1 displays the experimental configuration:

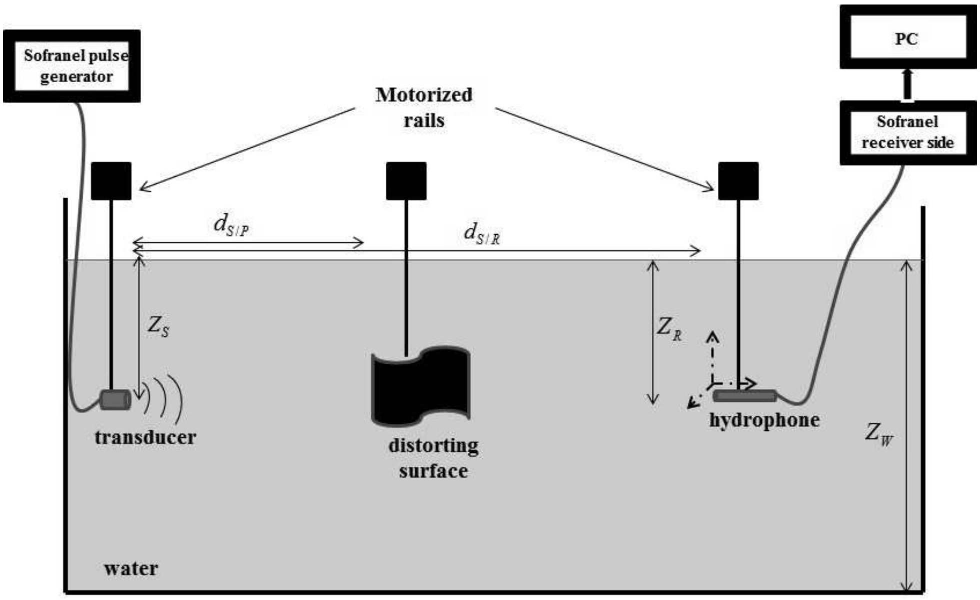

Fig. 1: Experimental configuration.

As represented in Figure 1, each experiment was depending on which distorting surface we were using. Different types of surface were used: a plano-concave acoustic lens (L1), a Fresnel-type acoustic lens (L2) and two wax plates presenting a plane surface on the source side and a sinusoidal surface on the receiver side (P2 and P4). Table 1 gathers the properties of these elements.

Properties	*Lens L1*	*Lens L2*	*Plate P2*	*Plate P4*
Dimensions				
Radius [mm]	120	120	-	-
Length [mm]	-	-	305	295
Width[mm]	-	-	205	190
Height [mm]	22 - 25	22 - 25	15.5 ± 1.5	15.5 ± 1.5
Oscillation Period [mm]	-	-	26	10
Oscillation Amplitude [mm]	-	-	2	1
Physical Properties				
Density [g/cm^3]	1.27	1.27	0.980	0.980
Longitudinal Sound Speed [m/s]	2700	2700	1975	1975
Shear Wave Sound Speed [m/s]	1430	1430	772	772
Attenuation [dB/cm]	3	3	2.5	2.5

Table 1: Properties of Distorting Surfaces.

We will now present some results of ray tracing simulations on the surfaces described in Table 1. Due to the aperture of the beam emitted by transducers, different distances $d_{S/P}$ were considered: for the acoustic lens, the distance was $d_{S/P} = 0.30\ m$, on the other hand for the wax plates, the distance was $d_{S/P} = 1\ m$ in order to account for several periods of oscillation of the surface. As depicted by Figure 2, the propagation of rays through the acoustic lens L1 induces refraction and we can observe the appearance of a focal point. On the other hand, since the wax plates P2 and P4 only present oscillations in the vertical direction, the propagation of the rays is not affected by the presence of the plate in the $x-y$ plane. In the case of the lens L1, the behaviour of the rays in this plane is very comparable to that of the rays in the $x-y$ plane. The observation differs for the two plates: the oscillations at the surface of the plates imply refraction of the rays and several focal points are observable. This property is very interesting since internal waves are known for presenting a vertical correlation length smaller than the horizontal correlation length, confirming the idea that our experiment can model their effects. We can deduce from the simulation results that the acoustic lenses L1 and L2 will present a high number of eigen rays localized at the focal point of the lens, whereas propagating the rays through the wax plates induce the appearance of many focal points, meaning that high number of eigen rays can be measured at several hydrophone positions.

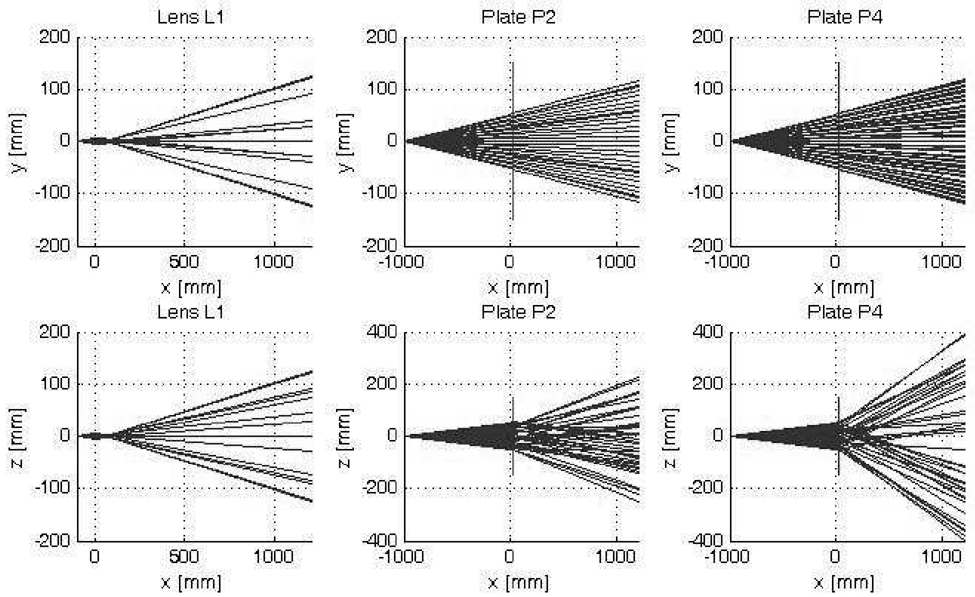

Fig. 2. Ray Tracing Routine Results.

3. EXPERIMENTAL RESULTS

The results from two different experiments are studied in this section.
First, we transmitted a signal through the unperturbed medium (fresh water), through the acoustic lens L1 and then, through the Fresnel type lens L2. In this experiment, that we will call Experiment 1, the distance $d_{S/R}$ was 0.52 m and the distance $d_{S/P}$ was 0.10 m. We measured the signal on a hydrophone moving along a line of 0.2 m with 1 mm steps, realizing a virtual horizontal array.

The second experiment, denoted Experiment 2, consists of sending the signal through the unperturbed medium, the wax plate P2 and the wax plate P4. In this case, we measured the signal realizing a virtual vertical antenna and a virtual horizontal antenna. Both present a length of 0.2 m with 1 mm steps and both are centred on the transmitter position.
Figure 3 displays the temporal envelop – the magnitude of the Hilbert transform – or the signal recorded by the antenna. Comparing the unperturbed signal with the signal propagated through the acoustic lenses confirms the idea of strong distortion of the signal at the centre of the antenna.
Figure 4 presents the same quantity in the case of Experiment 2. We observe distortions of the envelop of the signal in the case of the vertical antenna measuring the signal after propagation through the wax plates. The horizontal antenna does not present such fluctuations of the envelop in the three cases presented here.

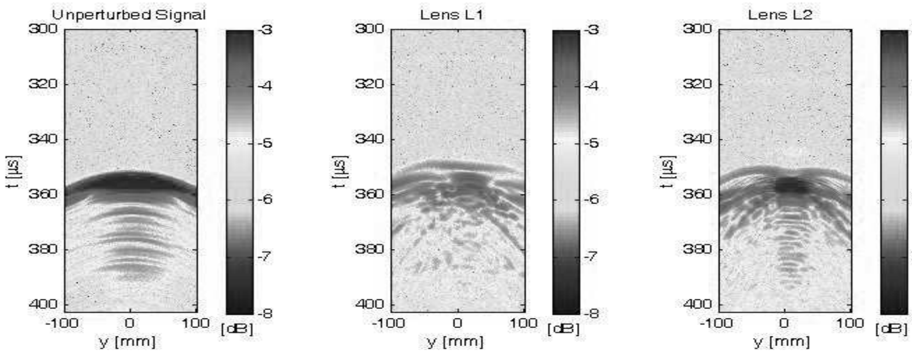

Fig. 3. Signal Envelop – Experiment 1.

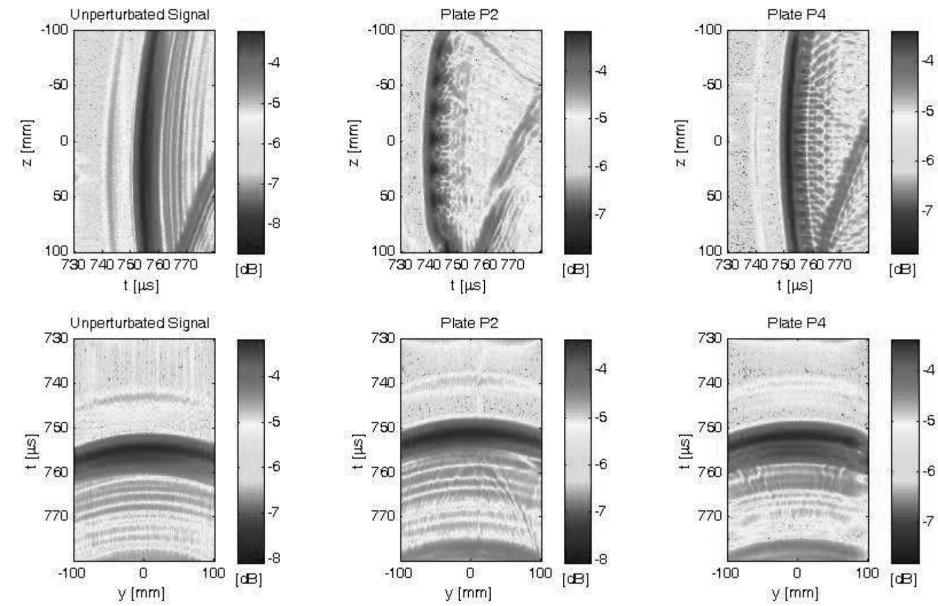

Fig. 4. Signal Envelop – Experiment 2.

The influence of the distortions of the signal is measured using a classical spherical two-dimension beam forming (or focalization) algorithm. Figure 5 displays the results for Experiment 1 and we observe strong distortions of the focalization output in the case of propagation through the lenses L1 and L2. Indeed, local maxima are observable, which means that the source position detection criterion is very sensitive to a threshold selection.

Degradation of the array gain has occurred. Figure 6 shows the output of the focalization algorithm for the data of Experiment 2. We observe fluctuations of the results especially in the case of propagation through plate P2. The performance of the detection routine applied to the data measured through plate P4 does not present high degradation, as compared to the unperturbed case. In the case of the horizontal array, the three figures are almost undistinguishable, meaning that the perturbations in this direction do not affect the performance of the antenna.

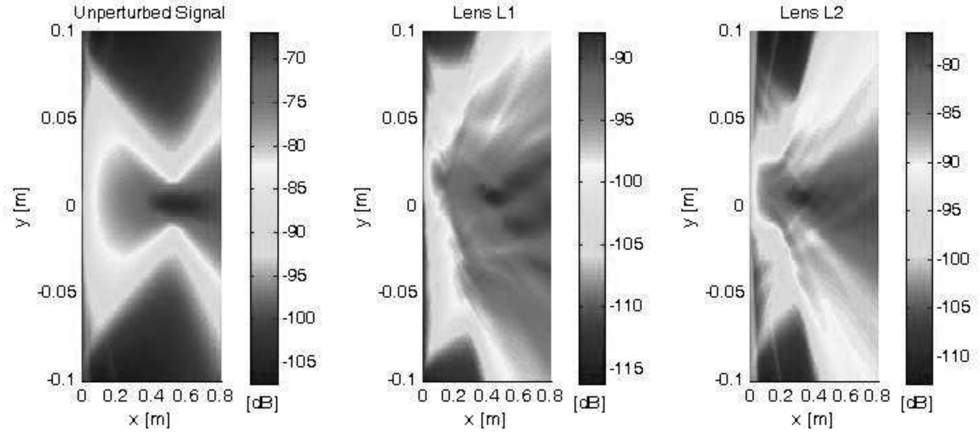

Fig. 5. Focalization Algorithm Output – Experiment 1.

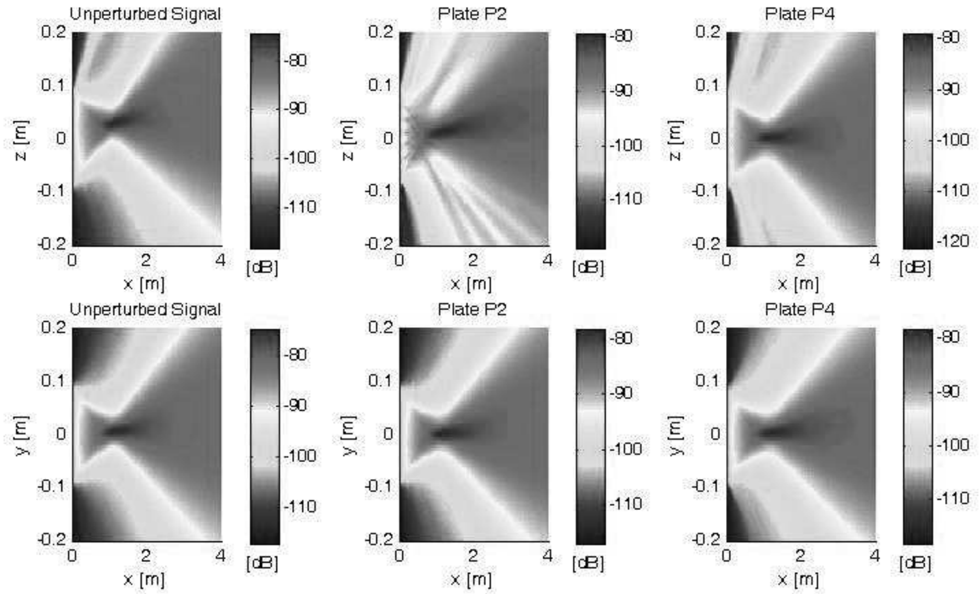

Figure 6. Focalization Algorithm Output – Experiment.

4. CONCLUSION

We presented a novel approach to measure the influence of spatial fluctuations of the propagation medium on antenna performance. An analytical study and the development of simulation tools, such as a ray tracing program, allowed us to establish reproducible scaled experiments translating in a well-controlled artificial facility the effects of physical phenomena such as linear internal waves. The principle of these measurements is to emit high frequency pulses through distorting surfaces (acoustic lenses, wax plates) and to measure the signal on a moving hydrophone, which allows us to simulate an array. The influence of the distortions of the signal was measured using a focalization algorithm. The acoustic lenses induce degradation of the antenna performance, so does the plate P2. The wax plates characteristic is to produce distortion of the signal in the vertical direction but not in the horizontal direction, which can be related to the anisotropy of linear internal waves. The next step of our work is to relate directly the experimental measurements with dimensionless parameter and define fluctuations regime corresponding to a given experimental configuration.

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